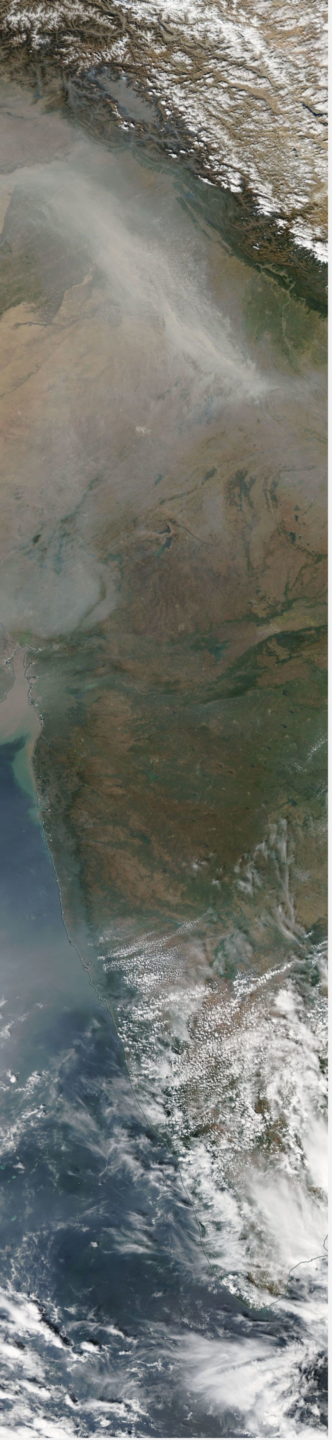


National Aeronautics and
Space Administration

ARSET
Applied Remote Sensing Training
http://arset.gsfc.nasa.gov
@NASAARSET

Theoretical Basis for Converting Satellite Observations to Ground-Level $PM_{2.5}$ Concentrations

Pawan Gupta

Satellite Remote Sensing of Air Quality: Data, Tools, and Applications

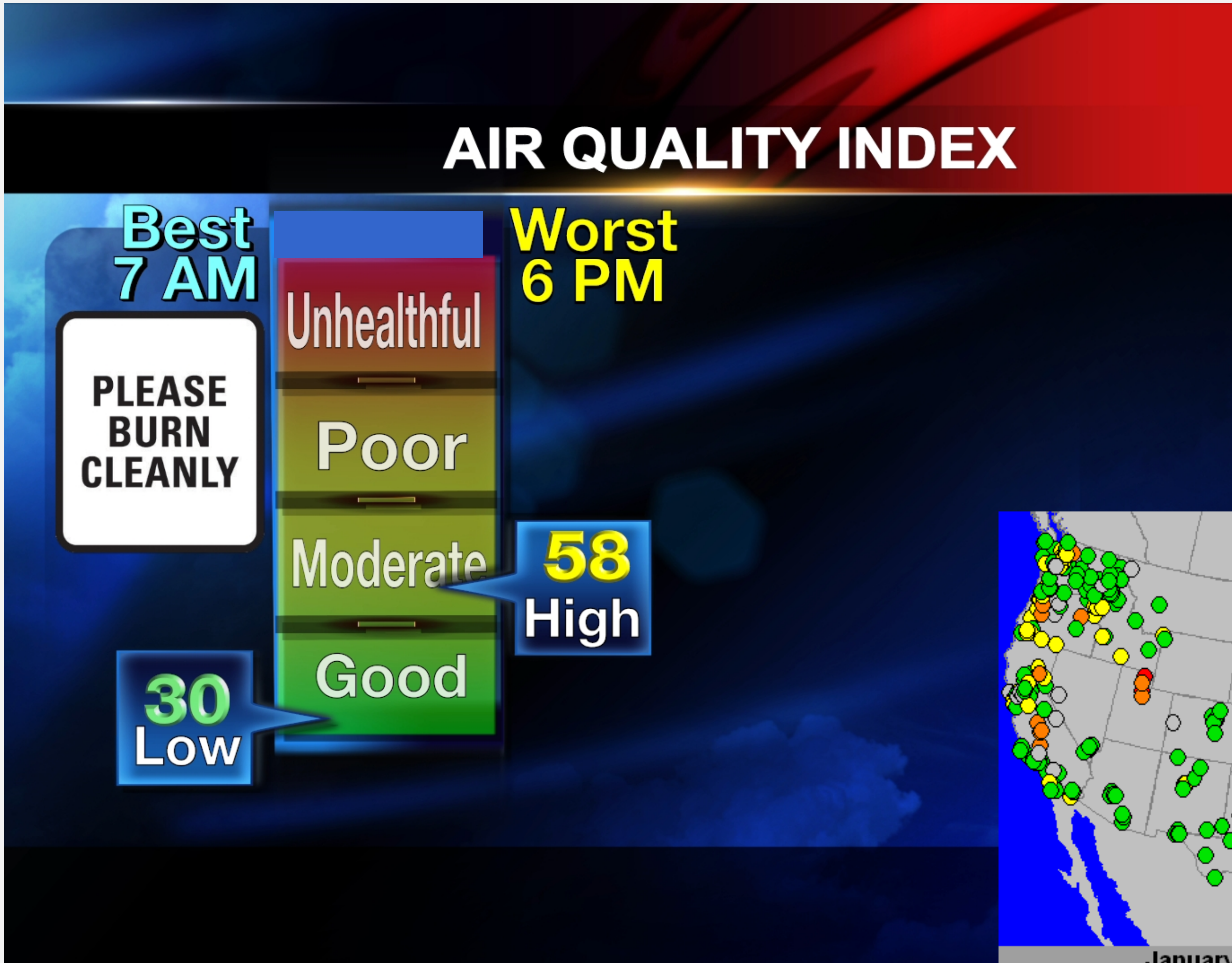
Tuesday, May 23, 2017 – Friday, May 26, 2017
Indian Institute of Tropical Meteorology, Pune, India

Objectives

By the end of this presentation, you will learn to:

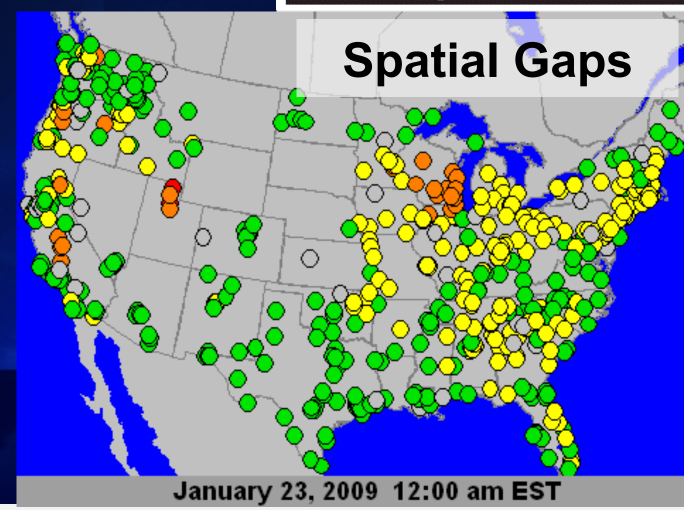
- Estimate $PM_{2.5}$ mass concentration at the surface level ($\mu g m^{-3}$) while using satellite derived Aerosol Optical Depth (AOD) at visible wavelengths

What are we looking for? And why?

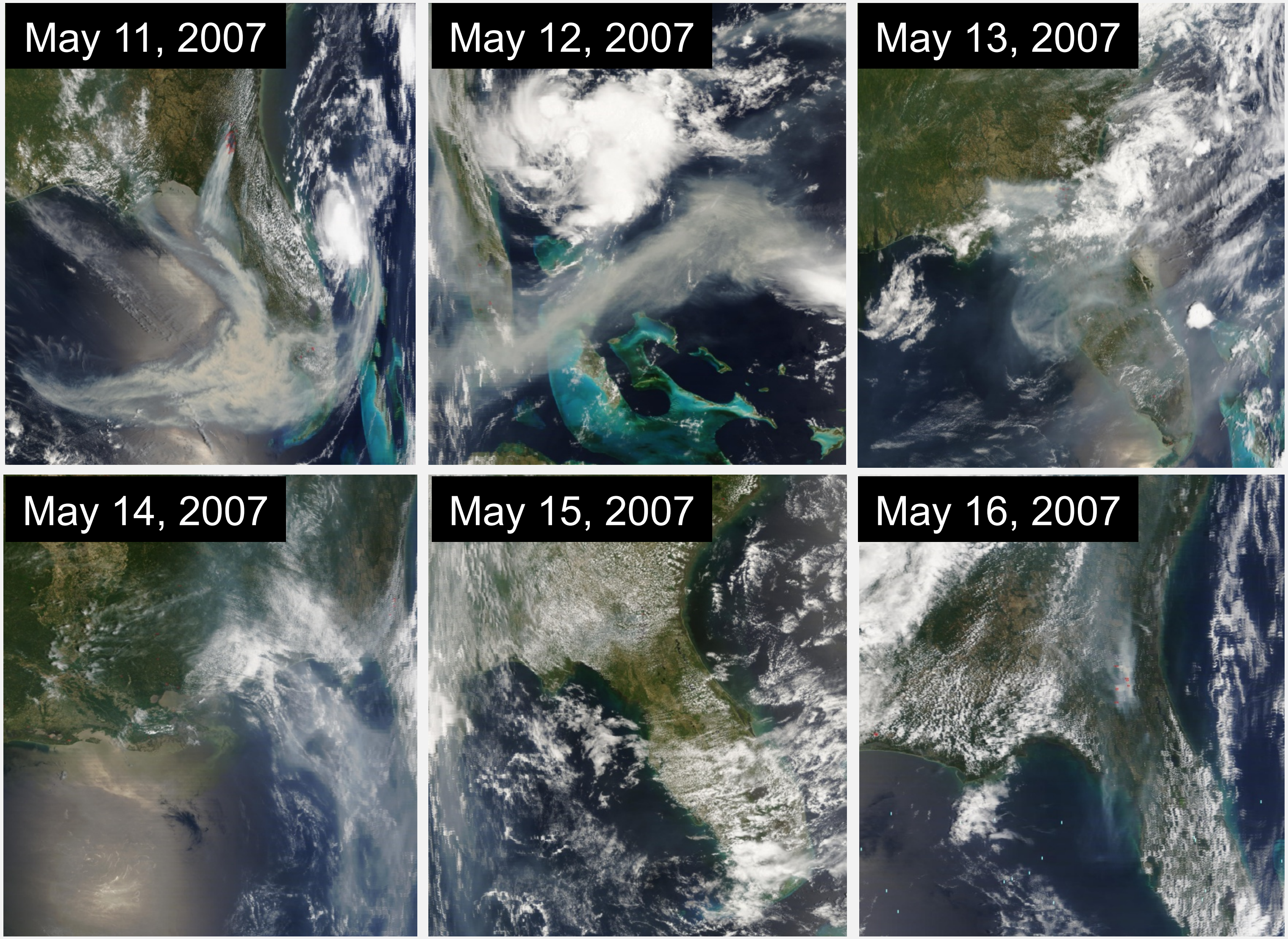


AIR QUALITY INDEX

Air Quality Index (AQI) Values	Levels of Health Concern
0 to 50	Good
51-100	Moderate
101-150	Unhealthy for Sensitive Groups
151-200	Unhealthy
201-300	Very Unhealthy
301 to 500	Hazardous

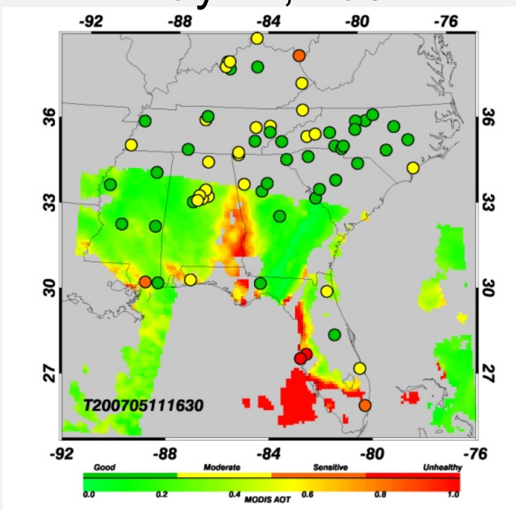


MODIS-Terra True Color Images

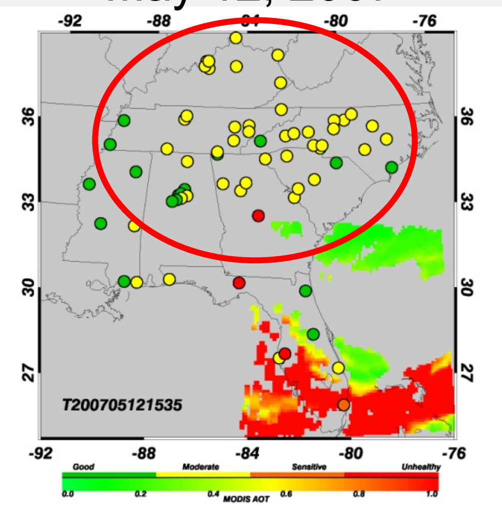


MODIS-Terra Aerosol Optical Thickness

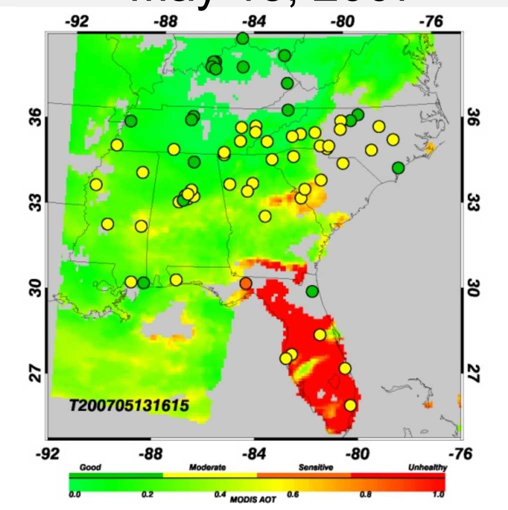
May 11, 2007



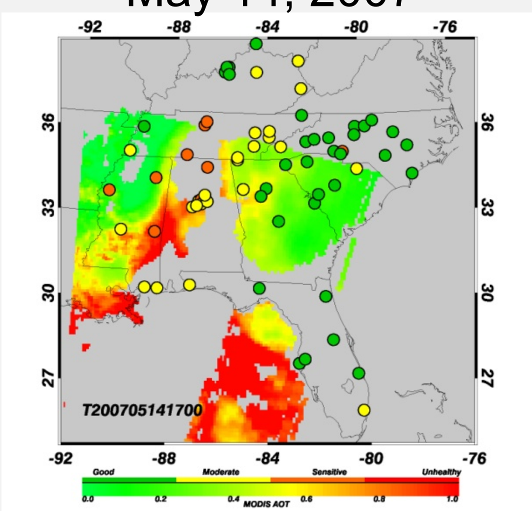
May 12, 2007



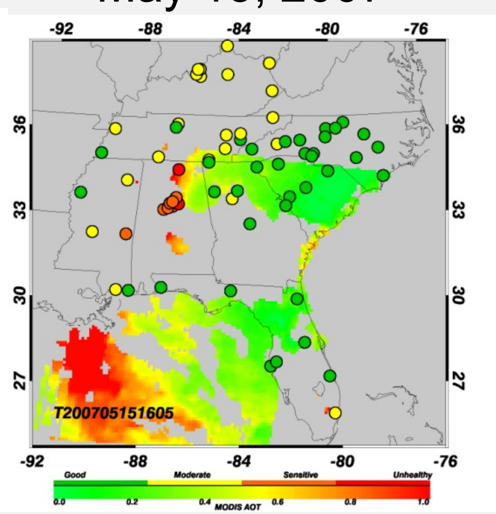
May 13, 2007



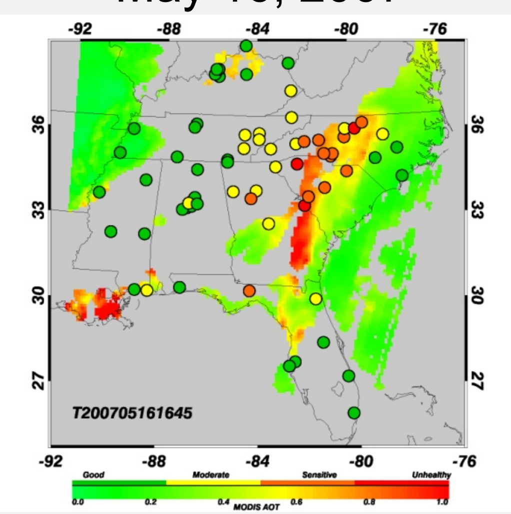
May 14, 2007



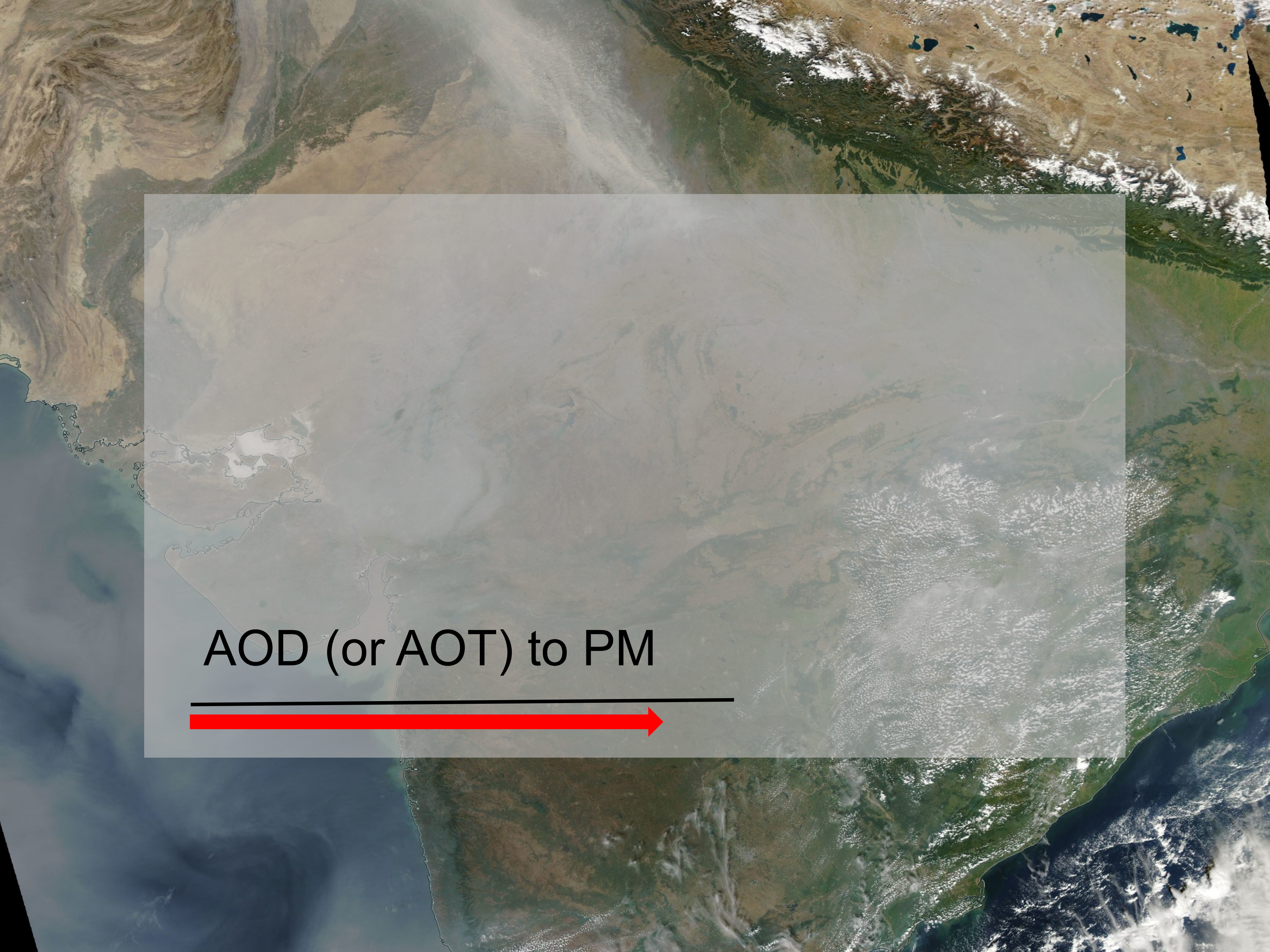
May 15, 2007



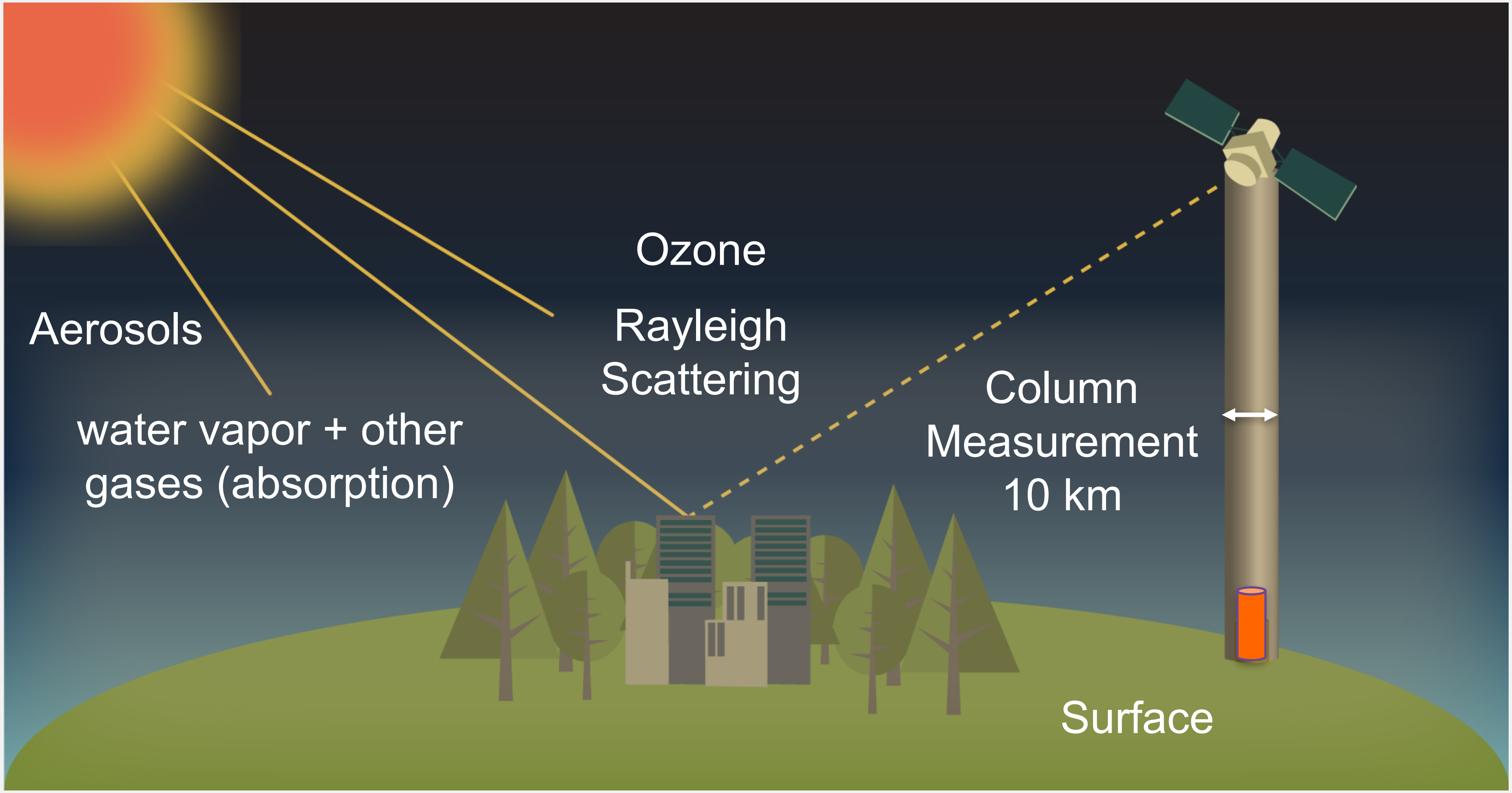
May 16, 2007



AOD (or AOT) to PM



What do satellites provide?



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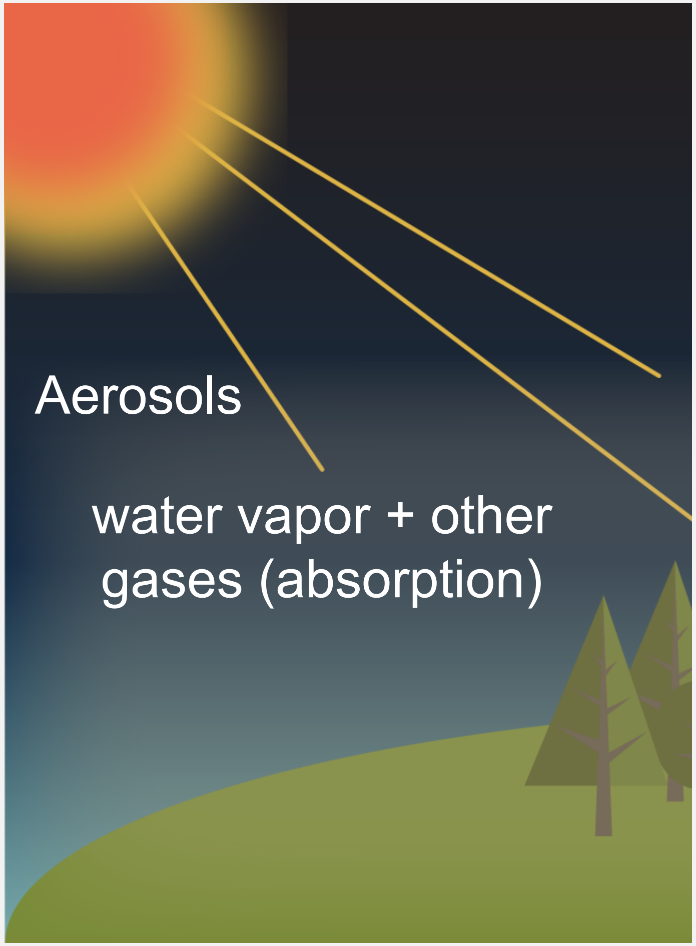
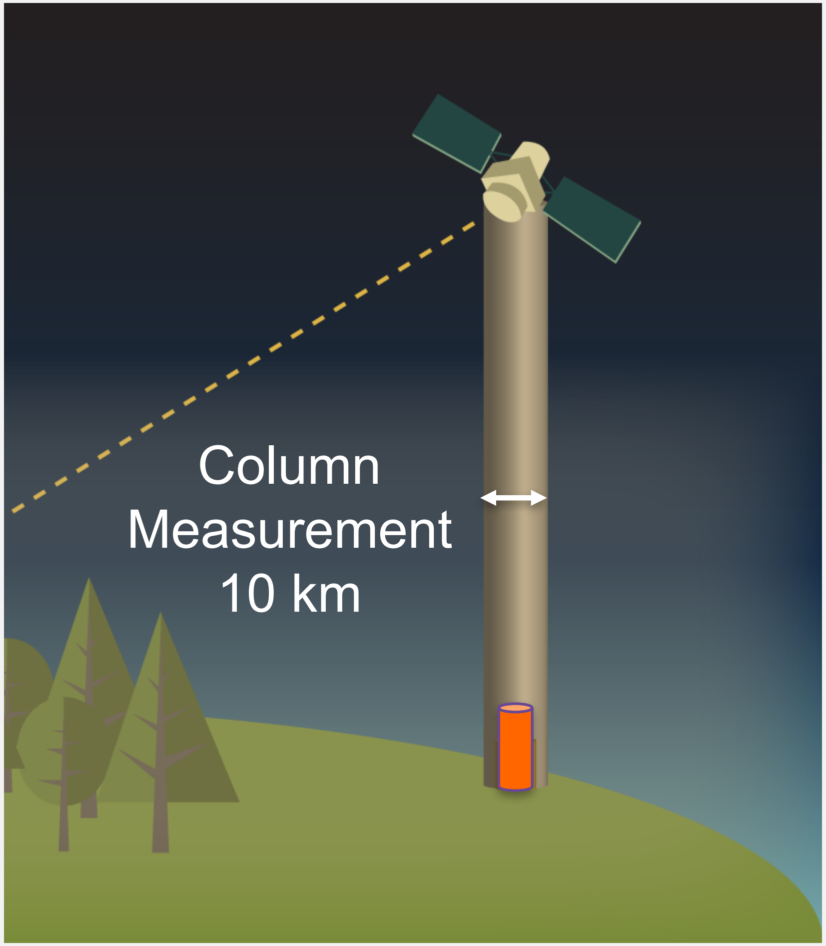


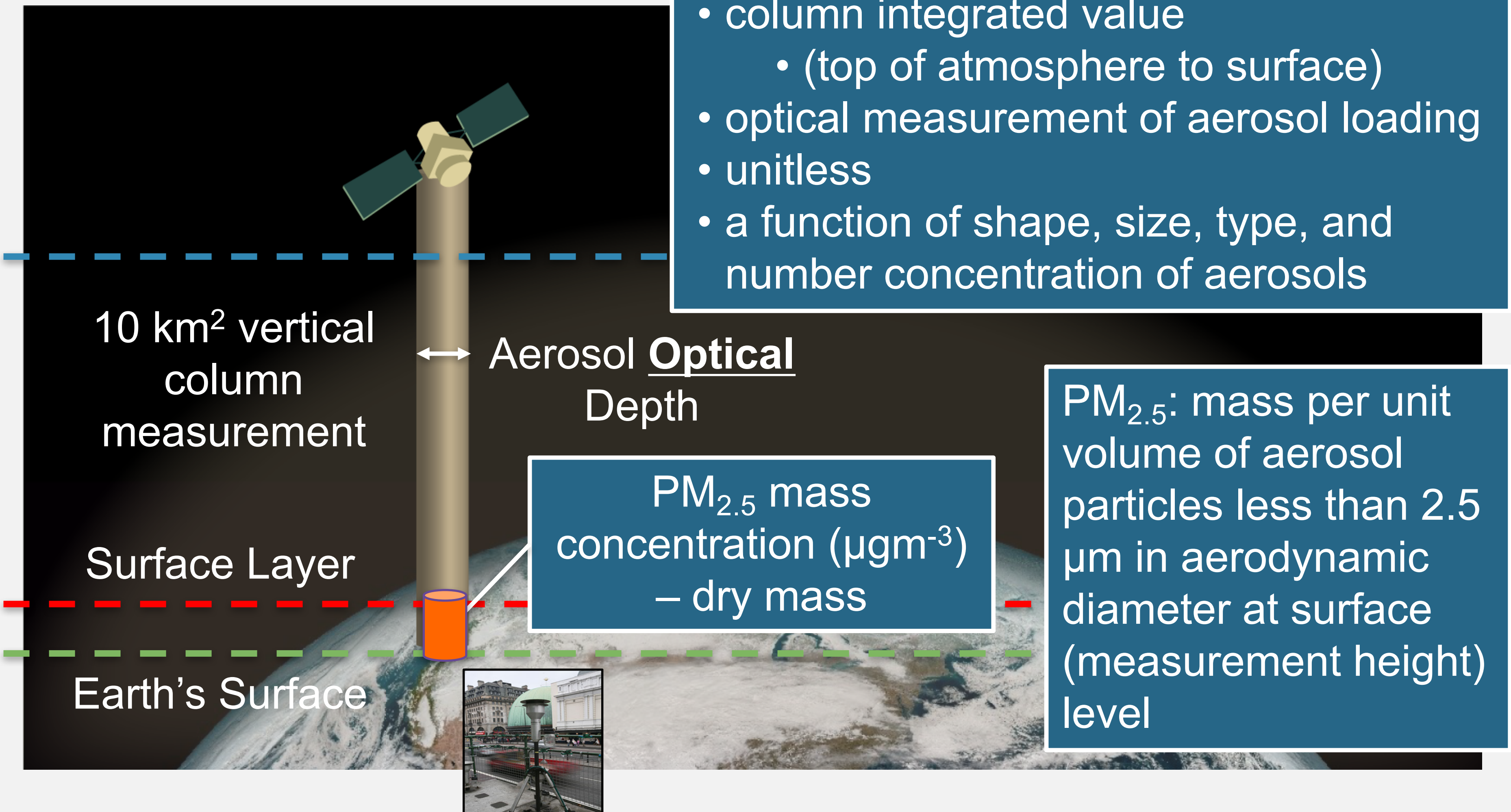
What do satellites provide?



Satellite vs. Ground Observation

AOD:

- column integrated value
  - (top of atmosphere to surface)
- optical measurement of aerosol loading
- unitless
- a function of shape, size, type, and number concentration of aerosols

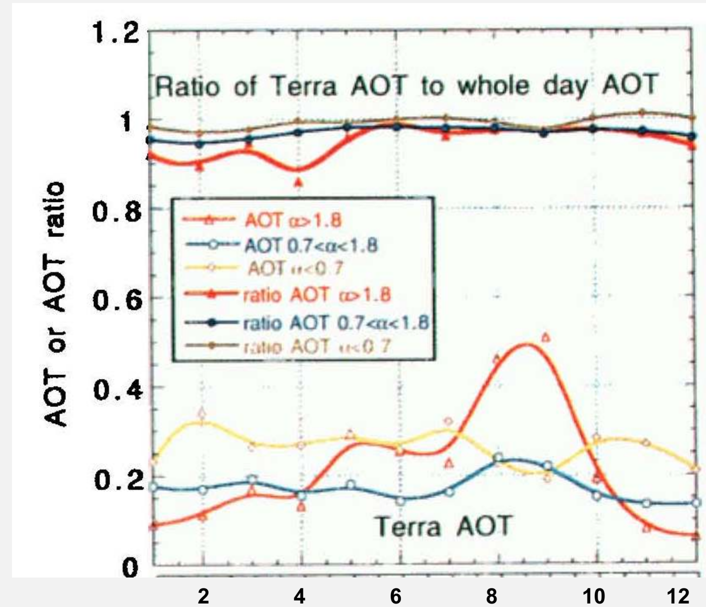


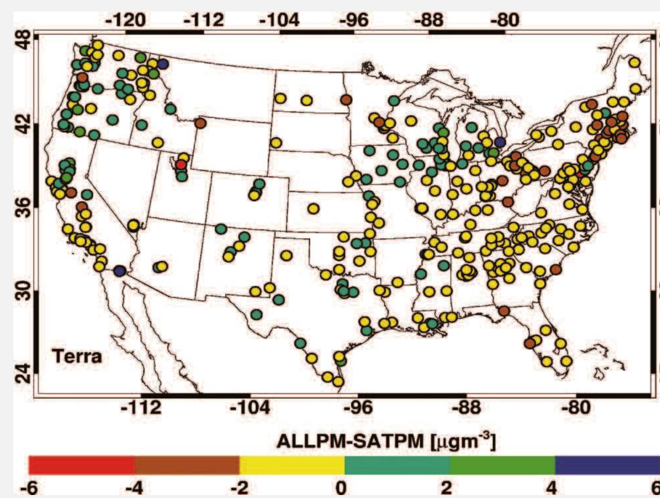
$PM_{2.5}$ mass concentration (μgm^{-3}) – dry mass

$PM_{2.5}$: mass per unit volume of aerosol particles less than 2.5 µm in aerodynamic diameter at surface (measurement height) level

Support for AOD-$PM_{2.5}$ Linkage

- Current satellite AOD is sensitive to $PM_{2.5}$
  - –Kahn et al. 1998
- Polar-orbing satellites can represent at least daytime average aerosol loadings
  - –Kaufman et al. 2000
- Missing data due to cloud cover appear random in general
  - –Christopher and Gupta 2010





Remote Sensing of Aerosols

AOD-PM Relationship

Assuming cloud-free skies, a well mixed boundary layer with no overhead aerosols, and aerosols that have similar optical properties*, AOD and $PM_{2.5}$ can be related by this equation:

$$C = \frac{4\rho r_e}{3Q} \times \frac{f_{RH}}{H_{PBL}} \times AOD$$

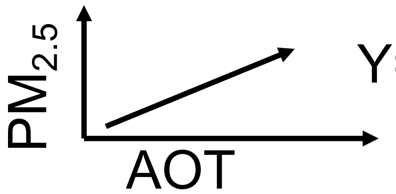
- C: $PM_{2.5}$ mass concentration
- ρ: aerosol mass density
- r_{eff}: particle effective radius
- Q: extinction coefficient
- H_{PBL}: mixing height
- *f (RH)*: how aerosol scattering changes with changing relative humidity

Hoff, R. & Christopher, S., 2009

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

Two Variable Method

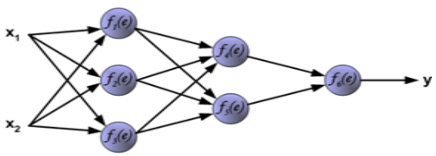


Y=mX + c

Multivariable Method

$$PM_{2.5} = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

Artificial Intelligence



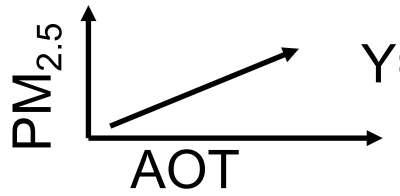
MSC

$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface aerosol concentration}}{\text{Model AOD}} \times \text{Retrieved AOD}$$

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

Two Variable Method



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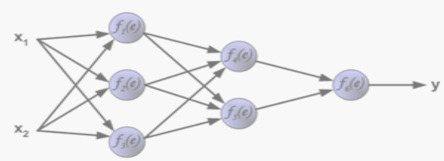

MSC

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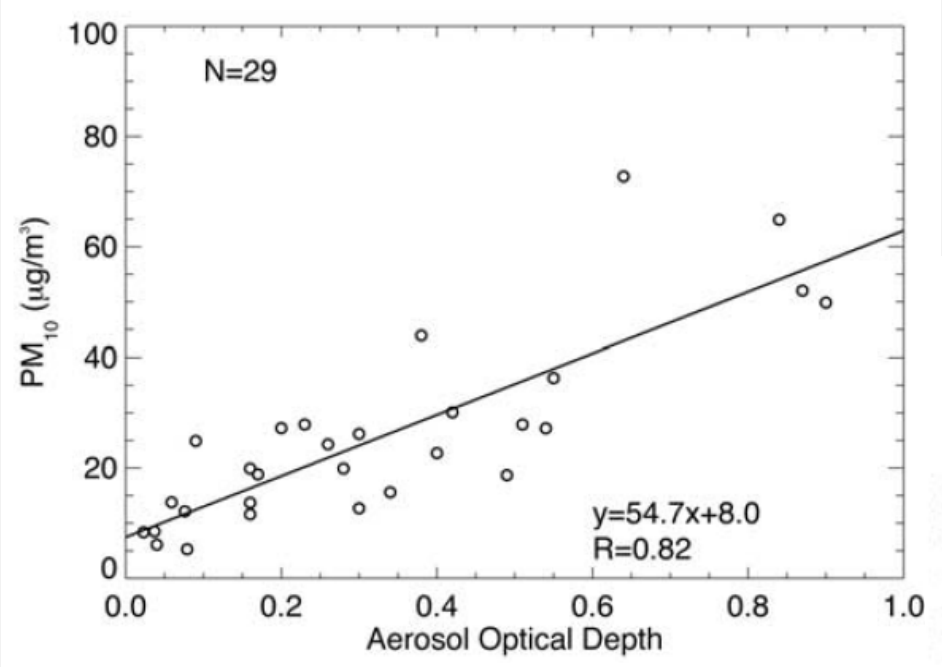
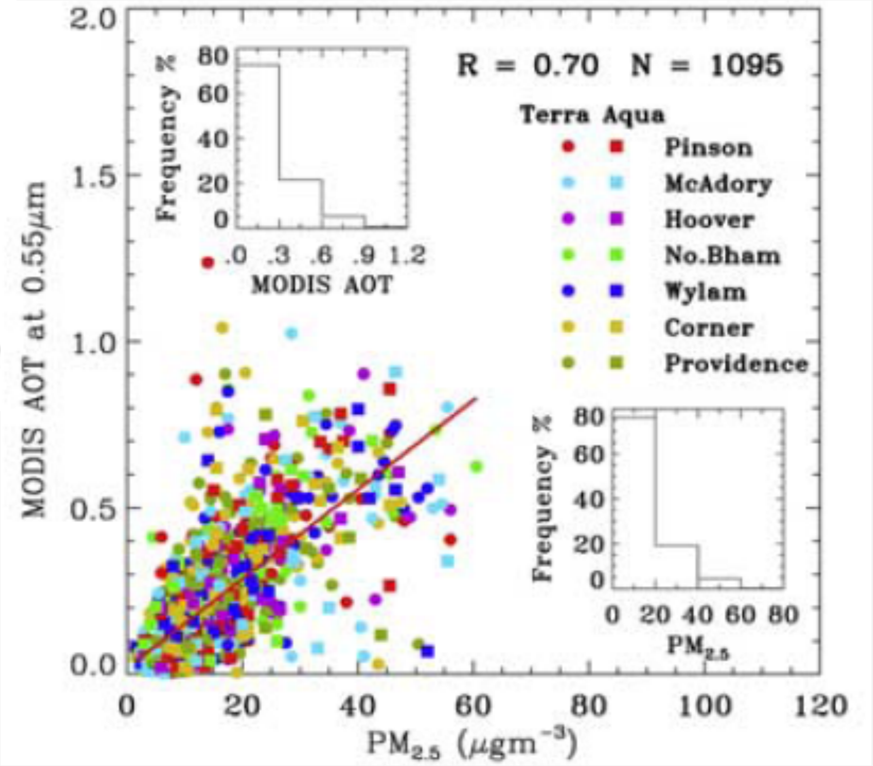
Simple Models from Early Days

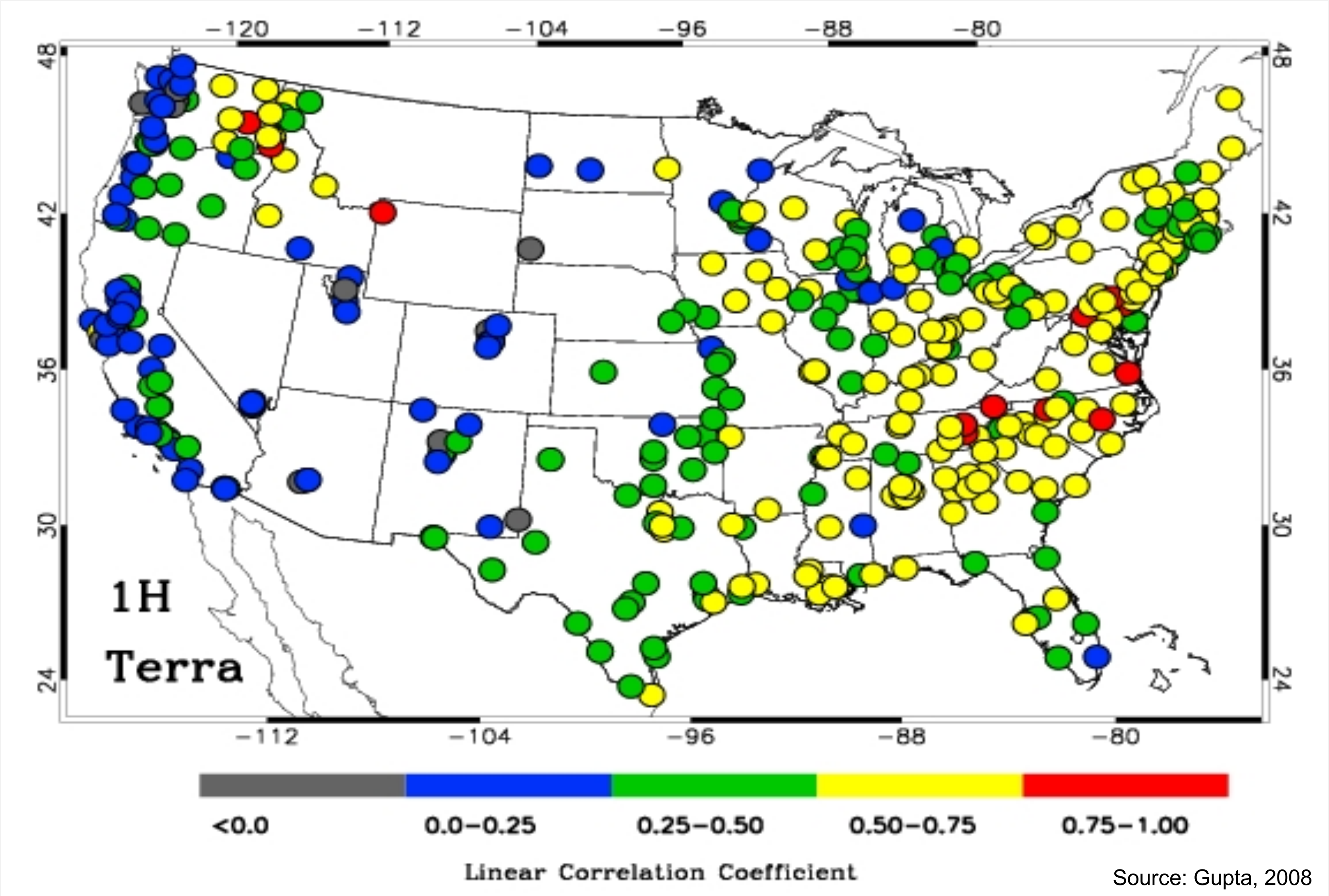


Source: Chu et al., 2003



Source: Wang et al., 2003

AOD-$PM_{2.5}$ Relationship



Source: Gupta, 2008

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

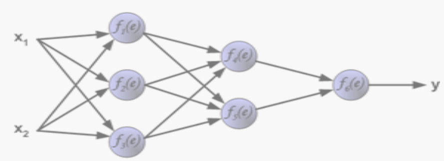
Two Variable Method

$$Y = mX + c$$

Multivariable Method

$$PM_{2.5} = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

Artificial Intelligence

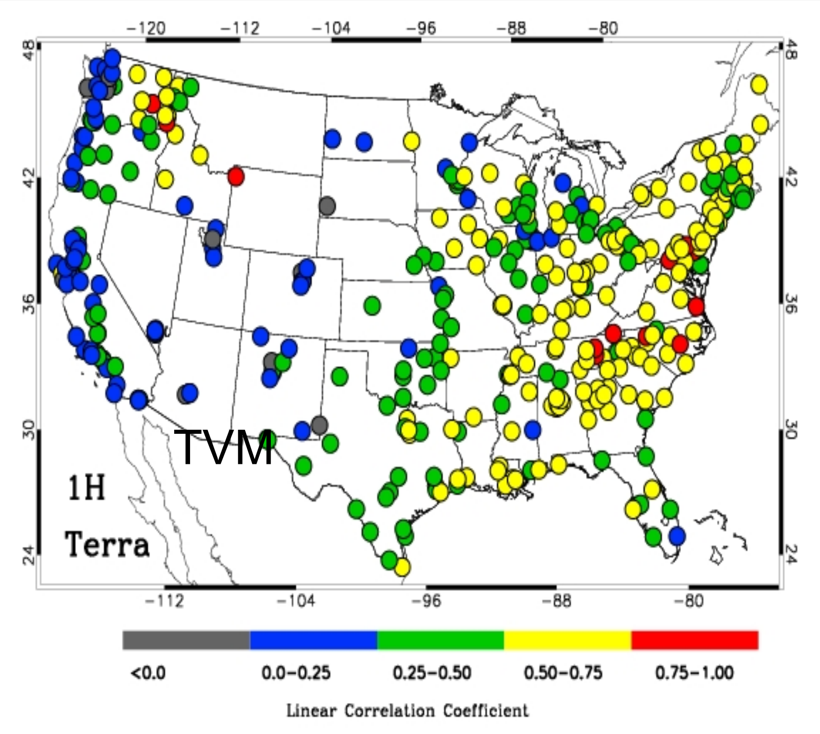


MSC

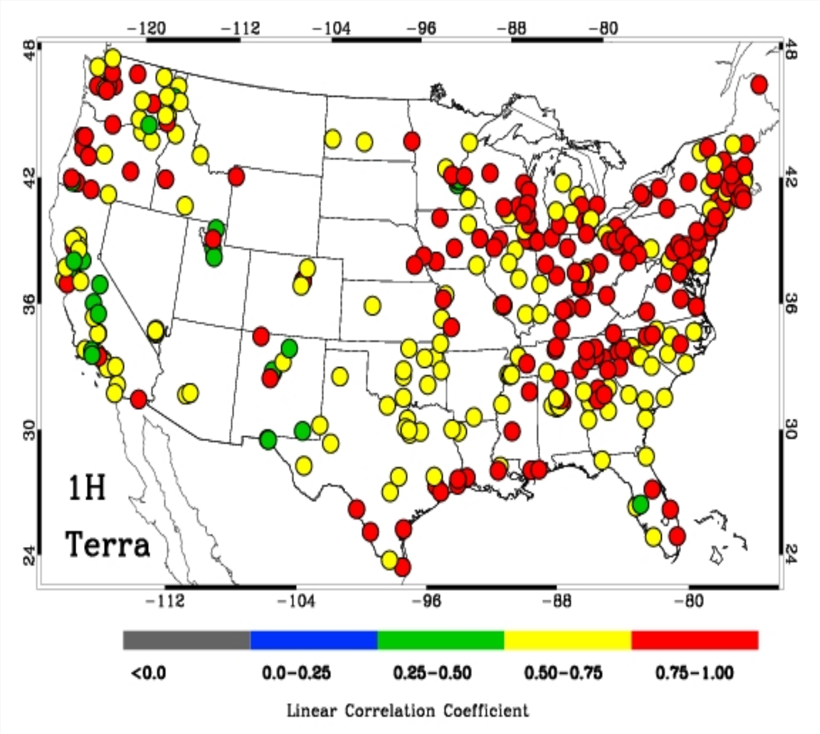
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface aerosol concentration}}{\text{Model AOD}} \times \text{Retrieved AOD}$$

Multivariable Method

Predictor: AOD



Predictor: AOD + Meteorology



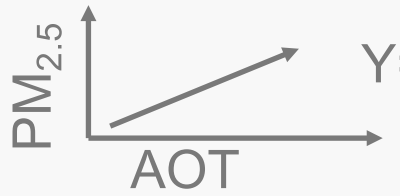
Linear correlation coefficient between observed and estimated $PM_{2.5}$

Source: Gupta, 2008

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

Two Variable Method

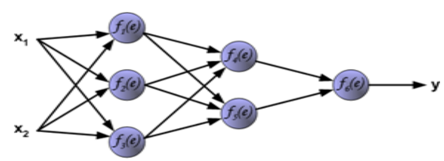


$$Y = mX + c$$

Multivariable Method

$$PM_{2.5} = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

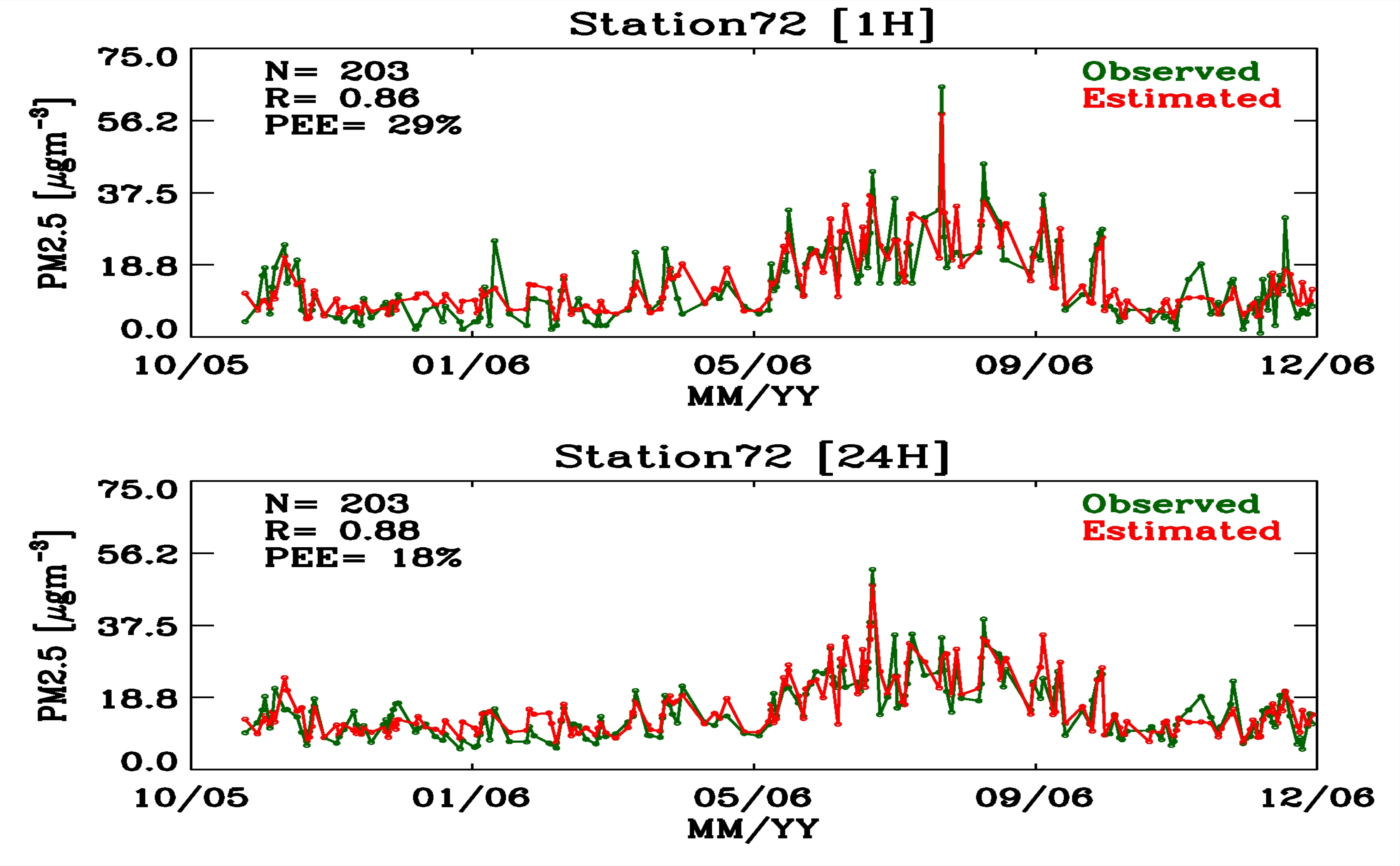
Artificial Intelligence



MSC

$$Estimated\ PM_{2.5} = \frac{Model\ surface\ aerosol\ concentration}{Model\ AOD} \times Retrieved\ AOD$$

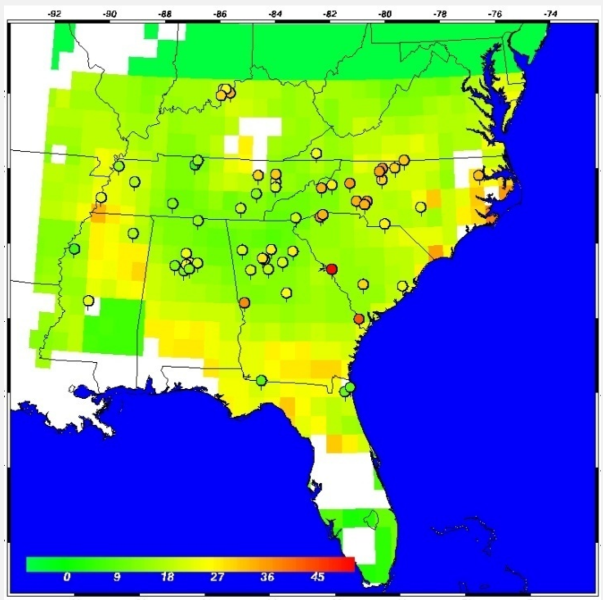
Time Series Examples of Results from ANN



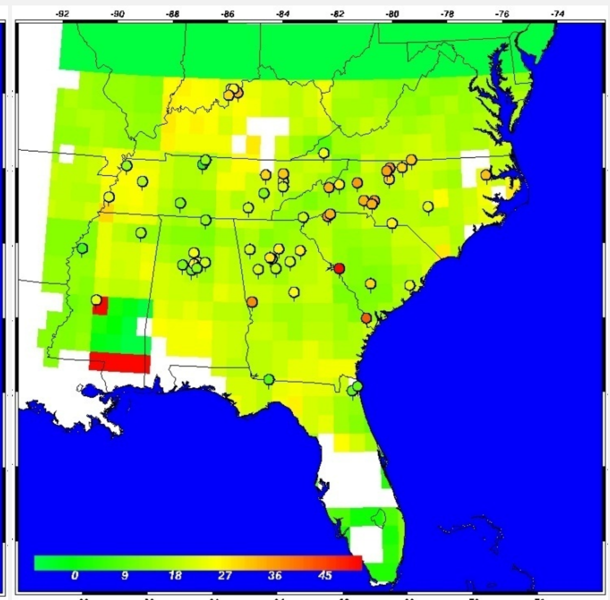
Source: Gupta, 2009

TVM vs. MVM vs. Artificial Intelligence

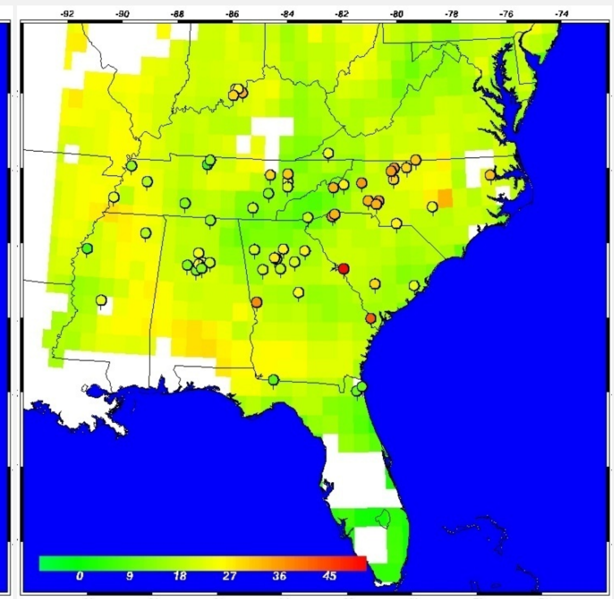
TVM



MVM



ANN

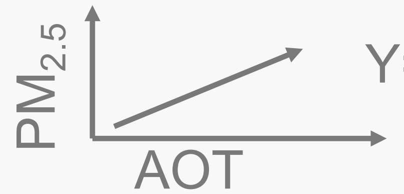


Source: Gupta, 2009

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

Two Variable Method



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Multivariable Method

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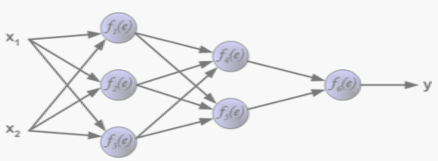


MSC

$$Estimated\ PM_{2.5} = \frac{Model\ surface\ aerosol\ concentration}{Model\ AOD} \times Retrieved\ AOD$$

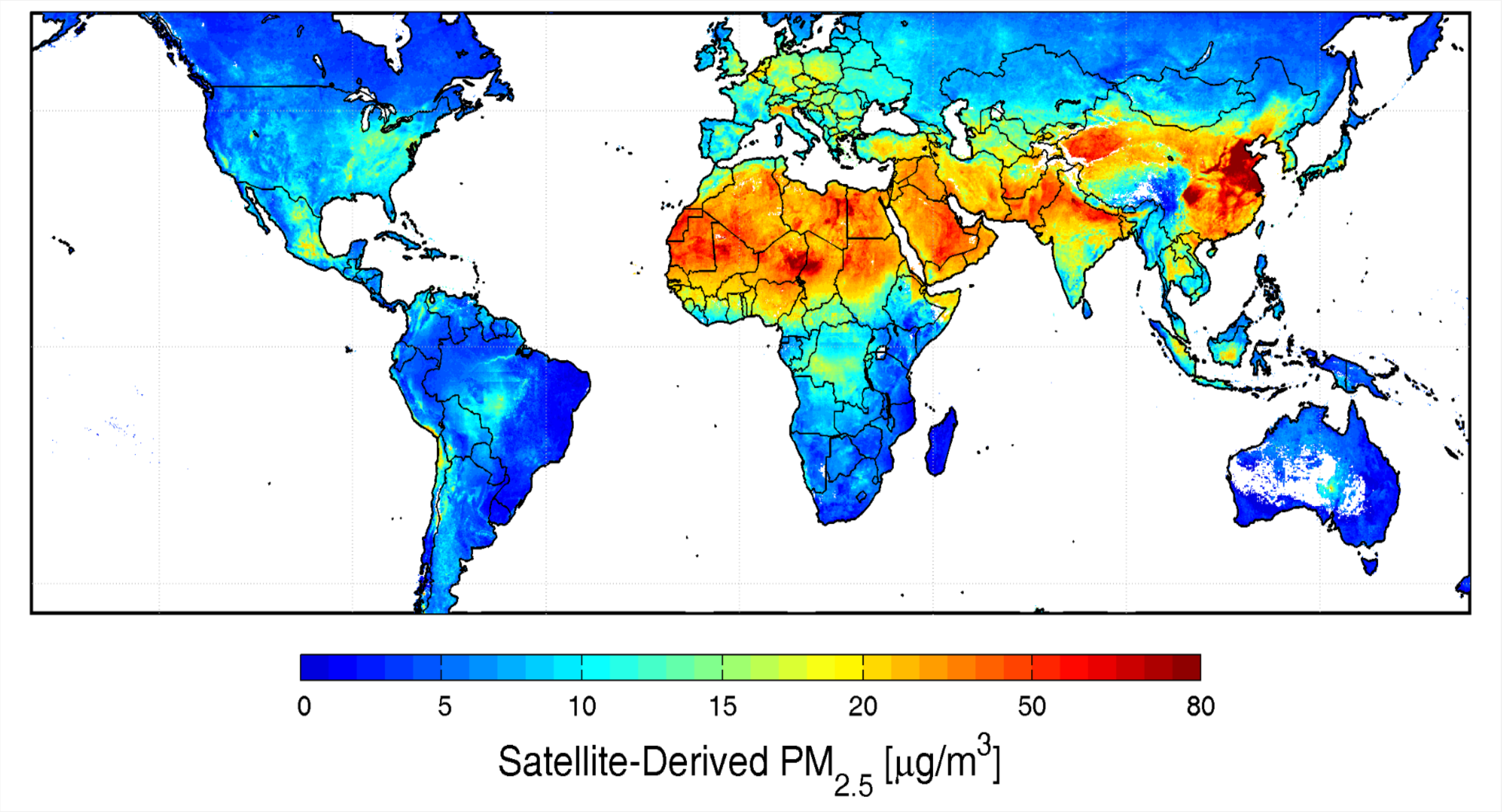
Scaling Approach

- Basic idea:
  - Let an atmospheric chemistry model decide the conversion from AOD to $PM_{2.5}$
  - Satellite AOD is used to calibrate the absolute value of the model generated conversion ratio

- Satellite-Derived $PM_{2.5} = \left(\frac{PM_{2.5}}{AOD}\right)_{Model} \times$ satellite AOD

Source: Liu et al., 2006

Annual Mean $PM_{2.5}$ from Satellite Observations

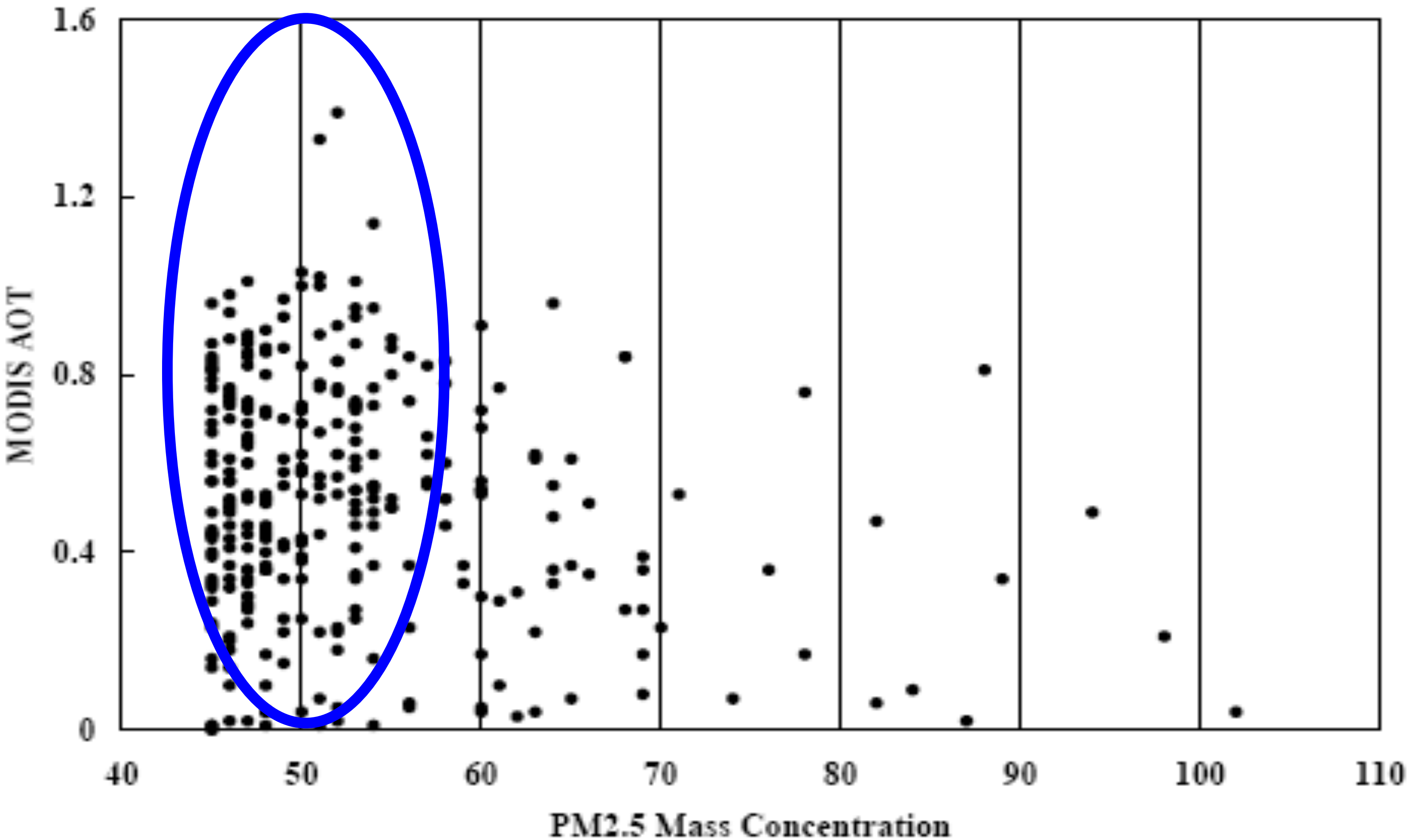


van Donkelaar et al., 2006, 2009

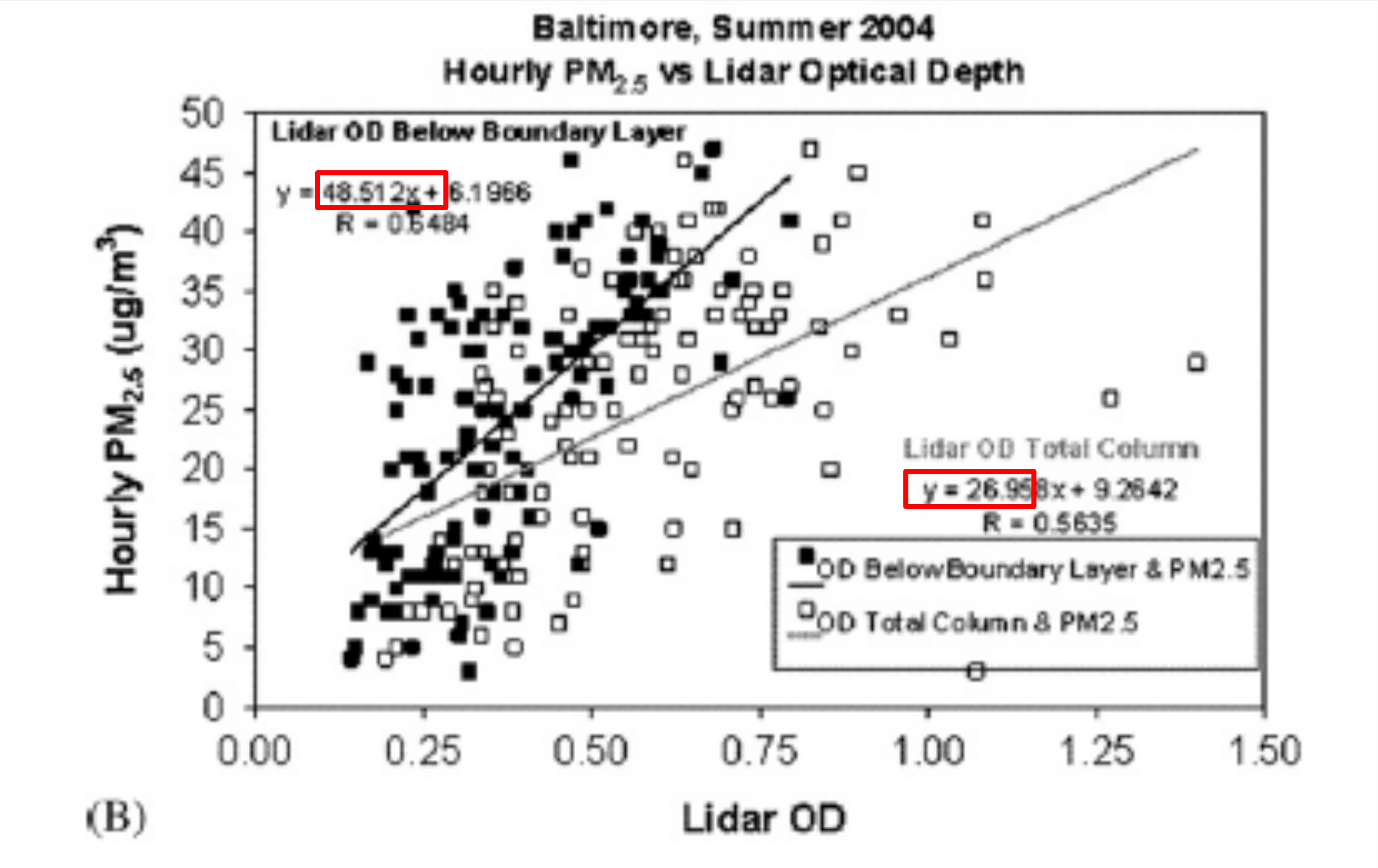
Questions to Ask: Issues

- How accurate are these estimates?
- Is the $PM_{2.5}$ – AOD relationship always linear?
- How does AOD retrieval uncertainty impact estimation of air quality?
- Does this relationship change in space and time?
- Does this relationship change with aerosol type?
- How does meteorology drive this relationship?
- How does the vertical distribution of aerosols in the atmosphere impact these estimates?

Limitation: Vertical Distribution of Aerosols



Vertical Distribution: Impact on AOD-$PM_{2.5}$

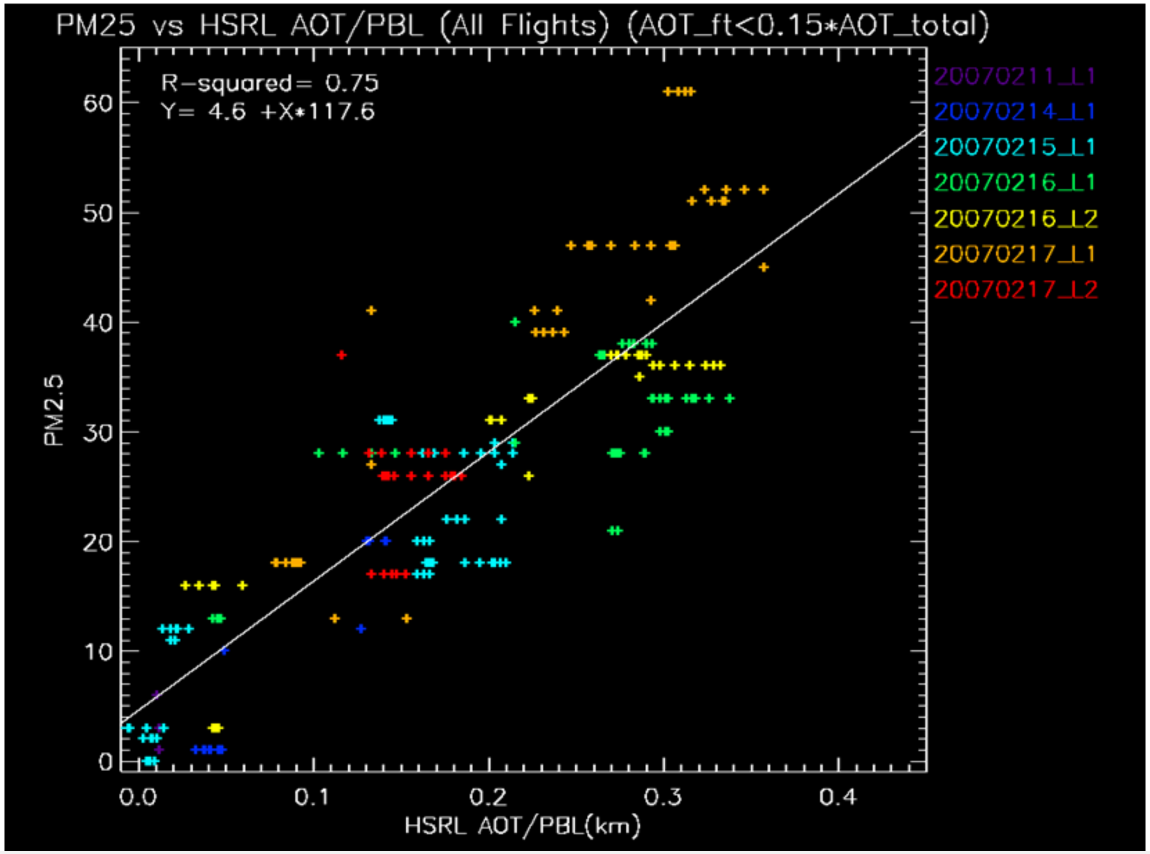


Source: Engel-Cox et al., 2006

Vertical Distribution: Impact on AOD-$PM_{2.5}$

Correlation of Surface PM2.5 with HSRL AOD / PBL, All Flights

- Normalizing AOD with boundary layer height significantly improves correlation with $PM_{2.5}$ (R^2 increases from 0.36 to 0.75)
- With accurate estimates of PBL height, AOD can be good proxy for $PM_{2.5}$



Source: Al-Saadi et al., 2008

Assumption for Quantitative Analysis

When most particles are concentrated and well mixed in the boundary layer, satellite AOD contains a strong signal of ground-level particle concentrations

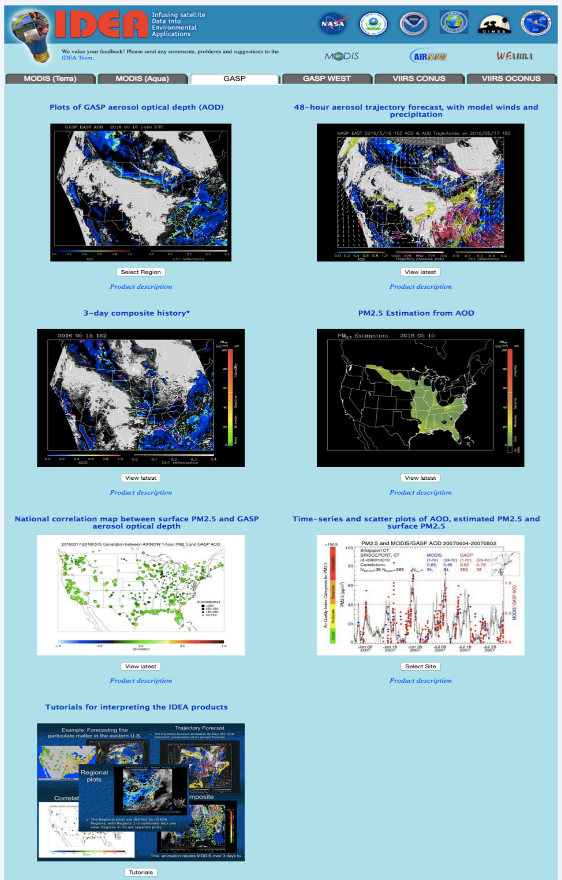
No textbook solution

Use of Satellite Data

- Currently for Research
  - Spatial distribution of $PM_{2.5}$ on regional to national level
  - Long term trends of $PM_{2.5}$
  - Model calibration, data assimilation and validation
  - Exposure assessment for health effect studies
- Near Future Research
  - Spatial trends at urban scale
  - Improved coverage and accuracy
  - Fused statistical-deterministic models
- For Regulation?

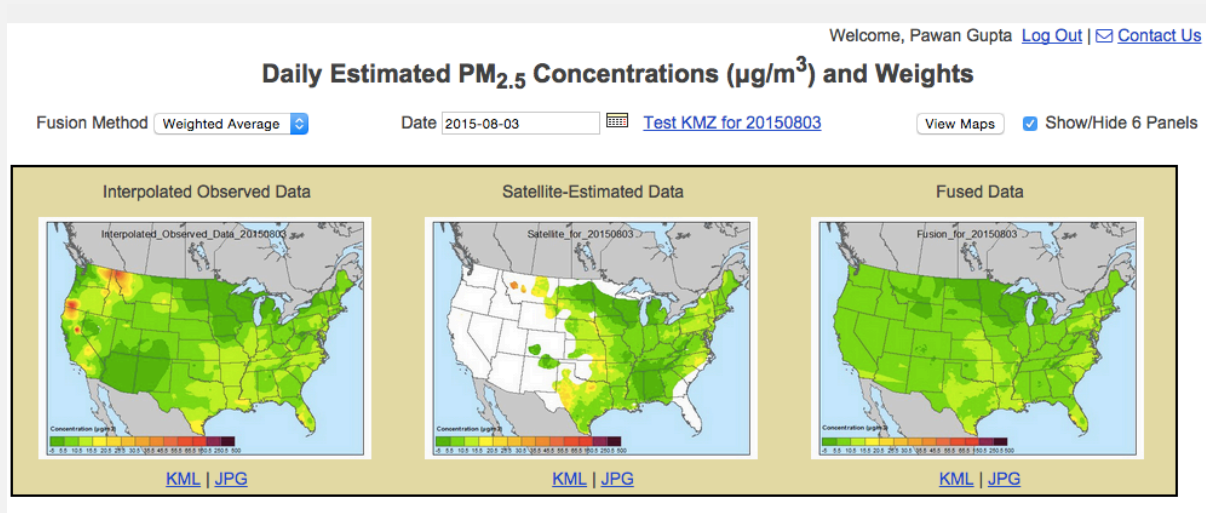
How Satellite Aerosol Data is Used

Infusing Satellite Data Into Environmental Applications



- Objective: near real-time product for state and local air quality forecasters
- Goal: improve accuracy of next day $PM_{2.5}$ AQI forecasts during large aerosol events

AirNow Satellite Data Processor (ASDP)



Suggested Reading

2009 CRITICAL REVIEW

ISSN:1047-3289 *J. Air & Waste Manage. Assoc.*
DOI:10.3155/1047-3289.59.6.645

R.M. Hoff

Remote Sensing of Partic
from Space: Have We Rea
Promised Land?

dard Earth Sciences

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IMPLICATIONS

Satellite measurements are going to be an integral part of the Global Earth Observing System of Systems. Satellite measurements by themselves have a role in air quality studies but cannot stand alone as an observing system. Data assimilation of satellite and ground-based measurements into forecast models has synergy that aids all of these air quality tools.

The use of the AOD as a measure for mass concentration has skill in some regions but less in others and does not provide a uniform way to measure aerosols across the United States. We discussed in Table 4 the range of mea-

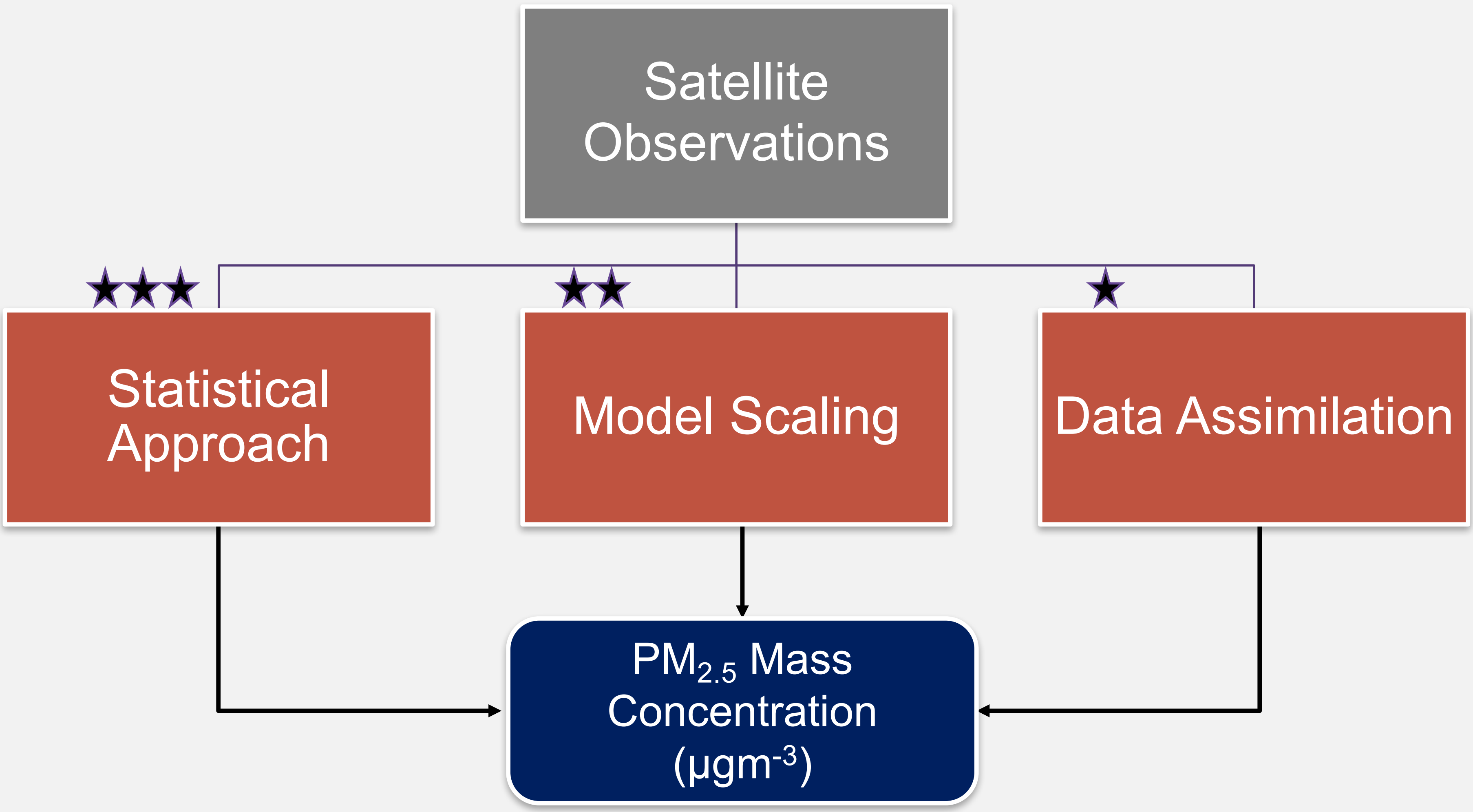
dards (NAAQS).[142] The 39-yr history of those standards parallels the time period that satellite meteorology and observations have developed and yet, to date, no satellite measurements have been used to quantitatively address the NAAQS. From the review conducted here, only one congres-

EPA has taken a satellite observations role for itself in the Exceptional Events Rule.[144] If a region can show conclusively that they are being impacted by an event (a fire, a dust storm, etc.) that is outside of their jurisdiction to regulate, the event can be flagged as a nonexceedance event. This provides a significant motivation for regional

ellite data possible in significant exceedances only. Applications such as event identification, transport, and atmospheric composition determination are strengths of satellite measurements. Where high precision is required (compliance monitoring, the "but for" test, and quantitative measurement of visibility effects on Class I areas), satellite data are presently of limited utility.

Although the desire for the use of satellite data for air quality purposes is widely stated, the reality is that many of the measurements have not yet met the promise that they can be operationally used for today's air quality monitoring requirements. Precision in measuring AOD is

Satellite Remote Sensing of $PM_{2.5}$: Summary



Questions and Discussion

- What are three differences between AOD and $PM_{2.5}$ mass concentrations?

- What are three advantages of using satellite observations for $PM_{2.5}$ air quality monitoring?

- What are the pros and cons of using a scaling approach over the regression method?

Suggested References

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Tour of IDEA

Accessing Near Real-Time Satellite Data for U.S. Air Quality

- Air Quality Case Study
  - Fires in Canada and Smoke Transport over U.S.
    - June 09, 2015
  - Buffalo Fires, Wyoming
    - August 13, 2016

- Tools
  - IDEA: http://www.star.nesdis.noaa.gov/smcd/spb/aq/
  - eIDEA: http://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea/

Questions